THE "GULF OF MEXICO" LATE HOLOCENE SEA LEVEL CURVE

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ABSTRACT

Beach ridge plains on four sides of the Gulf of Mexico produced a new sea level history for late Holocene time: St. Vincent Island, Florida panhandle; Sanibel Island, lower peninsula of Florida; Mesa del Gavilan, east of Brownsville, Texas; and Isla del Carmen, in the state of Campeche, Mexico.

On St. Vincent Island there are roughly 400 data points (elevation and relative age), each taken from a position on a beach ridge or in a swale. These ridges and swales can be grouped in sets; some sets stand high, and some are low. Some of the set boundaries mark rises or drops of sea level. Detailed topography, relative moment measures (sand grain size distribution), and linear-suite grain-size data all show the same changes: two drops and two rises since about 5,000 B.P. Vertical uncertainty is one meter or less; time uncertainty is less than about 50 years. High stands exceeded the present level by 1.0 m (3.3 ft) or more, and low stands were below it by 1.0 m (3.3 ft) or more. The latest change in this range was a rise, about 800 years ago.

The three other areas were compared with St. Vincent Island. The fit is very good, as far back as the record goes in each case. Areas of measurable (known) warping have been avoided in this work. Because the four study localities are spaced at distances up to more than 1,200 km (745 mi) apart, it does not seem possible that unknown warping could have affected the results. The large number of data points within each small area, the large distances between study sites, and direct use of the data (rather than statistical surrogates) provide very great assurance for the reliability of the result. The curve produced in this fashion has been designated the "Gulf of Mexico" late Holocene sea level curve.

Late Holocene sea level did NOT approach the present position asymptotically, but fluctuated both above and below it, with an apparent period of very roughly 2,000 years. The rate of short-term change was about 5 cm/yr (2 in./yr). Small changes (<50 cm; <20 in.) and very slow changes (e.g., < one cm/yr; < 0.4 in./yr) are not visible in the present data set.

INTRODUCTION

The history of sea level change, over the most recent 5,000 – 6,000 yrs, has been the subject of much debate. There have been three main schools of thought: (1) sea level rose steadily, from a low position in Wisconsin time, approaching asymptotically its present level, without significant variations (Morner, 1982); (2) there were various short ups and downs, including at least one position 1.0 meter (3.3 ft) or more above the present level, roughly 4,000 – 6,000 years ago (Morner, 1982); (3) the noise (of various kinds) in the data is so great that no meaningful details can be obtained at all (Kidson, 1982, p. 144 – 145).

Clearly, if one collects data from (a) presumably stable areas, (b) deltas undergoing major subsidence, (c) actively rising continental margins, (d) tilted coast lines, and (e) perhaps a few other special cases, and then mixes all of this information in an uncritical way, the result will be first-class confusion. However, a reasonably large data pool can be acquired within certain small areas, so that one does not need to combine these categories. Within such a small area, there should be no confusion as to uplift, subsidence, warping, or any other such effect.

In the present paper, one small study area will be described, and data from three others will be summarized. All four are located on the shores of the Gulf of Mexico (Fig. 1), yet no two of them are as close to each other (in a straight line) as 400 km (240 mi), the next closest spacing is 1,000 km (600 mi), and the maximum spacing is more than 1,200 km (720 mi). They truly "encircle" the Gulf of Mexico, and agreement between any two of them cannot be said to be local. On the other hand, each is truly small, and hence should yield internally consistent results.

The four localities, in clockwise order, are the following: St. Vincent Island, in the Florida Panhandle (on the north-eastern shore of the Gulf of Mexico); Sanibel Island, on the lower west coast of the Florida Peninsula (east-central shore); Isla del Carmen, in the state of Campeche, Mexico (southern shore); and the Boca

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Chica (Mesa del Gavilan) locality, east of Brownsville, Texas (western shore; Fig. 1). Areas known to have been warped or deformed have been avoided.

ST. VINCENT ISLAND: HISTORY OF WORK

A sea level curve for St. Vincent Island was first presented by Stapor and Tanner (1977). This curve was based in part on a plane-table profile across the beach ridge plain on that island (Fig. 2). Differences in ridge set elevation (not individual crest heights), kitchen middens and other Indian sites, a ^{14}C date on a marine shell bed, and historical data were used to construct a history.

The published curve includes a high stand (+ 1 to 2 m; 3.3 to 6.7 ft) about 5,000 years ago, a low stand (−1 to −2 m; −3.3 to −6.7 ft) about 4,000 - 2,700 years ago, a high stand (+1 m or so; 3.3 ft) 2,700 - 1,700 years ago, a low stand (about −2 m; −6.7 ft) 1,600 - 1,000 years ago, and the present position since 800 - 1,000 years ago. This history includes three rises, two drops, and five intervals of "stability" [although it is recognized that the data available cannot identify changes in mean sea level of less than perhaps 50 cm (20 in.)].

St. Vincent Island gives no clues of tilting, warping, or faulting of any kind, but is nevertheless an area of only about 6 × 14 km (3.6 × 8.4 mi). Therefore the curve obtained in that study must represent what happened in terms of local sea level; the big question remaining is, does that curve reflect purely eustatic changes, or are there other components?

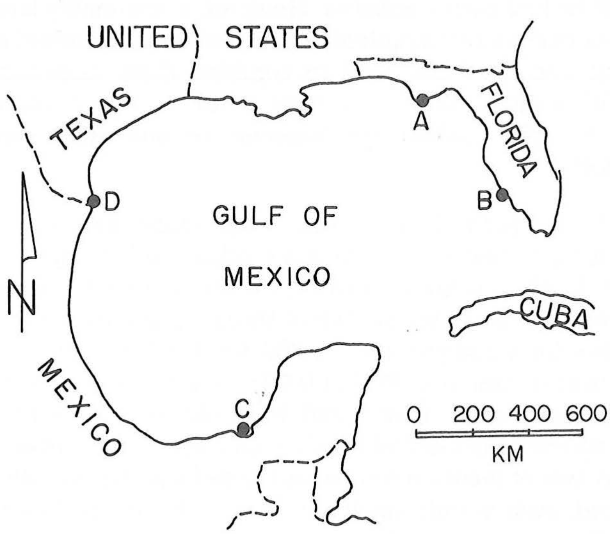

Figure 1. Outline map of the Gulf of Mexico region, showing the four study localities: A. St. Vincent Island, Fla. B. Sanibel Island, Fla. C. Isla del Carmen, in the state of Campeche, Mexico. D. Mesa del Gavilan, an island within Laguna Madre, near the southern tip of Texas. The wide spacing between study areas provides that no local effects are important to the resulting sea level history.

More recent work on the island, notably that of Demirpolat, Tanner and Clark (1986) showed that the basic information in the plane-table profile could be obtained in other ways (e.g., from air photo studies and from soil studies; Fig. 3), and that advanced statistical procedures (in this case, relative moment measures) could be applied to a large bank of sand grain size data to produce the same sea level curve developed by profiling. These procedures show how the grain size measures (mean, standard deviation, skewness, kurtosis), change within any one beach ridge set, both absolutely, and relative to the set-mean values of these parameters. The most useful of the relative moments were the relative standard deviation and the relative kurtosis. The relative kurtosis, for example, is calculated by dividing the sample kurtosis by the set-mean kurtosis. The relative standard deviation was obtained by a similar procedure. It should be kept in mind that each set has a distinctive set elevation.

The relative standard deviation and relative kurtosis changed value dramatically at every point where the other available information indicated a sea level change (Fig. 4-A). Furthermore, there is a hydrodynamic explanation for this phenomenon, based on the fact that a fairly abrupt change in sea level must mean an important modification of wave energy levels in the surf zone (at least until a new stable transverse profile is established; cf. Rizk and Demirpolat, 1986).

The grain-size data from the island can be exploited in still a different way, because samples from ridges in a time sequence constitute a linear suite (Tanner, in press, a, b). For this purpose, the ratio of mean/kurtosis (Mn/K; Fig. 4-B) was calculated for each sample in the linear system, and then 3-point moving averages were determined. This step minimizes ridge-to-ridge noise, but does not affect the ridge-set parameters (because there are 8 to 20 ridges per set). The Mn/K ratio identifies correctly all of the changes deduced from using the other methods, and gives R^2 values, for intervals of sea level change, of better than 0.95. That is, Mn/K identifies each sea level change, the direction of change, and the time required for that change, with high precision. This method also identifies correctly the intervals of little or no change.

Convergence of these different lines of evidence on a single result increases the assurance that the local sea level curve, obtained previously for the island, is essentially correct.

GEOMETRY OF THE SYSTEM

The beach ridges in the four study areas are highly regular swash-built features (Tanner, 1987). They occur in large numbers (scores to hundreds, on any one beach ridge plain) unlike the single massive ridges, typically five to 10 meters (16 to 33 feet) high, that are built elsewhere by repeated storm-surge activity. Although they may have small local eolian decoration, they are not dune ridges. Internal features are 70 – 100% swash bedding, at typical beach slope angles. The occasional tall ridge built by storm surf (NOT storm surge) to 2 – 4 m (6.7 to 13.3 ft) height is easy to identify in the field, and does not have to be confused with the rest of the nearby beach ridges.

Where they are numerous, swash-built ridges commonly occur in sets. Along any one transverse profile, the ridges within one set are consistent in height, spacing, and front slope. The rate of growth, where we have been able to determine this parameter for various intervals in historical time, is consistent from ridge to ridge within a single set.

The highly regular nature of swash-built beach ridge geometry and growth rates, along one profile and within one set, provides a large amount of information for the coastal specialist. The mean ridge height for a set of 10 or 20 ridges, built over an interval of centuries (depending on the rate), indicates sea level position for that interval and does not depend on storms (except for rare storm surf ridges). Boundaries between sets may or may not indicate a change in sea level position. Where adjacent sets have a measurable set-height difference a change in sea level is indicated. Where there is no such difference in set heights, one does not know whether there was a very small change in sea level, or perhaps some other effect having to do with the evolution of the offshore sand pool (Demirpolat et al, 1986).

The sequence, in a well-organized beach ridge plain (such as on St. Vincent Island, Florida) is unmistakable, and permits relative dates from one ridge to the next to be determined fairly closely, typically to better than 50 yrs. Only a few historical or radiometric dates are needed to construct a well-controlled history, because a simple beach ridge system such as this one is itself a calendar.

NATURE OF THE DATA

The sea level curve obtained on St. Vincent Island differs from other existing curves in several important ways. In the first place, it does not depend on single isolated points, or even on a statistical summary of such

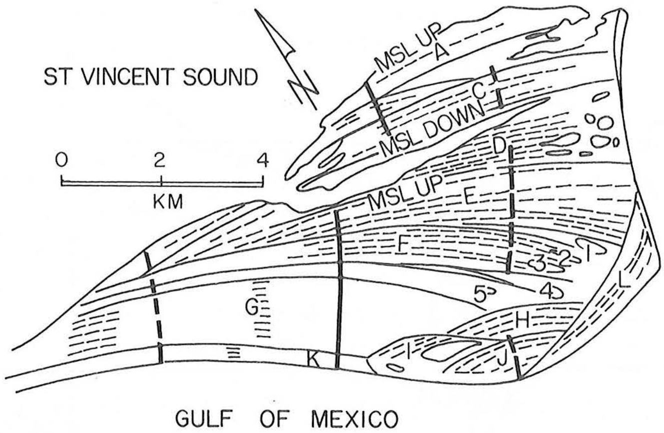

Figure 2. St. Vincent Island, Fla. Small arabic numbers identify selected lakes and ponds; capital letters refer to sets of beach ridges. There are about 200 beach ridges on the island. Heavy dashed lines are sample transects, where representative samples were collected for studying possible trends from one end of the island to the other. The heavy continuous line is a transect where each accessible and identifiable beach ridge was sampled.

points. In many studies, a single shell, or a small collection of shells, was dated, providing a single elevation and a single date: an isolated point. This point was then placed on a plot showing single points from other areas, near or far away. One has very little evidence for reliability, and there may be a great deal of disagreement between or among areas.

The work on St. Vincent Island produced a large number of points from a very small area. When the statement is made that Ridge Set D, on that island, stood 1 m (3.3 ft.) or more lower than older and younger sets, some 40 – 50 points (crests and swales) are being used. And when one notes that Set E stood 1 m (3.3 ft.) or more higher than adjacent sets, some 50 – 60 points are employed, not counting adjacent sets. There are 180 – 200 ridges on the island, hence 350 – 400 distinct topographic points, and most of these fall in an obvious time sequence (which, in this area, is not subject to uncertainty or rearrangement). Therefore any one position of the water surface was defined (in an area only a few kilometers, or miles, across) by dozens or scores of points, having a fairly narrow time range, with strict limits in each direction.

In the second place, the physical evidence for certain changes in mean sea level can be traced for tens to hundreds of kilometers or miles (for example, the high stand of the sea, at about +2 m (+ 6.7 ft), around 5,000 years ago: (Stapor, 1973). In the case where such a feature maintains its vertical position for such distances,

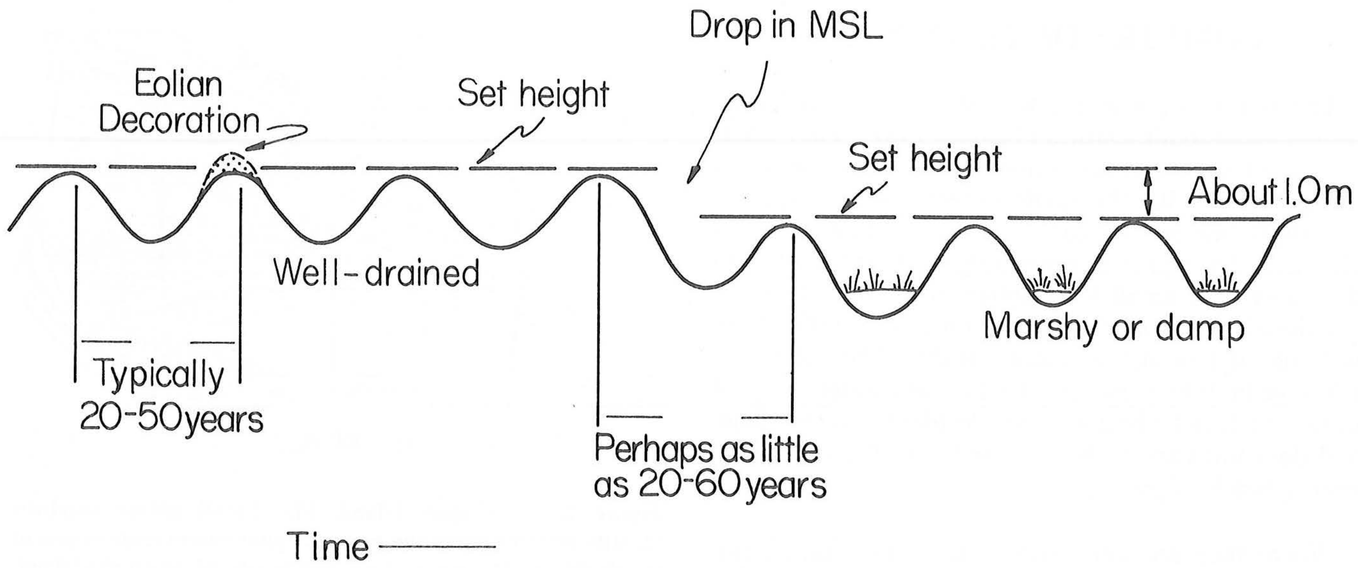

Figure 3. Differences between adjacent sets, where there is a discontinuity in vertical position. In the diagram, sea level dropped between the first and second sets. Differences show up as contrasts in vertical position, soil drainage and color, and sedimentological parameters. Local examples of eolian decoration are not important.

there is no longer very much possibility that it is "strictly local."

In the third place, key positions now can be correlated over distances exceeding 1,000 km (600 mi), as is discussed below.

And in the fourth place, the wealth of detail on a beach ridge plain permits interpolation (where limiting dates are available) down to the order of ten years: the average time interval between ridge and swale, on St. Vincent Island, is only some 5 – 20 years. This means that changes in mean sea level, recorded in the beach ridge data, took place in intervals as small as 20 – 50 years, but clearly less than 100 years.

Therefore the sea level curve derived from the St. Vincent project appears to be supported by dozens to scores of points for each segment. It likewise contains changes in level which are limited to less than a century, at rates equal to or more than 1 cm/yr (0.4 in./yr).

ISLA DEL CARMEN

The best evidence for sea level change, on this small island near the western edge of the state of Campeche, in Mexico, has been developed by Alvarez (1984, 1985) in the course of archeological work. He studied a site known locally as Los Guarixes (gwar-ee-SHAYS), near the eastern end of the island, and about 30 km (18 mi) east of the city, Ciudad del Carmen (at the western end; Fig. 5).

The island itself consists of two separate beach ridge plains: eastern, and western. Each started independently of the other, and each grew northward (into the Gulf of Mexico) and westward until they finally merged into one island. Closure of the inlet between them may have taken place in the XVII or XVIII century, according to old maps of the area showing two distinct islands (Alvarez, 1984, page 7 as well as his Fig. 6).

Alvarez reported a low sea level from about 1,900 years ago to about 900 years ago, and the present position since perhaps 700 years ago (1984, p. 8, p. 44; 1985, p. 69 – 70). He further cited similar results from the work of Roman Pina Chan and Agustin Delgado on the archeological site known as Jaina, on the western coast of the Yucatan peninsula.

There is a single published ^{14}C date from the island (Thom, 1969). This was taken from a sample collected on the lagoon side of the island, and hence it might represent the oldest ridge. However, the growth history of the western beach ridge plain has been such that one cannot make this decision with much assurance; the only clear statement that can be made is that some PART of the oldest ridge SET appears to be 2330 (+ or −95) years old. The two obvious sets on the western plain stand at two different levels: the older is higher, and the younger lower (but the latter shows an increase in elevation in its later history). If this single date (with no support) is valid, then there appears to have been a drop in sea level since some 2,300 years ago. This event must be placed prior to the archeological sequence obtained by Alvarez, giving a drop roughly 1,900 – 2,100 years ago. The subsequent rise has not been dated, but is

about half-way across the plain, hence perhaps approximately 1,000 B.P.

MESA DEL GAVILAN

Although the name includes the word "mesa" (table, or tableland), this small island has an average elevation of less than 1.0 m (3.3 ft). It is located east of Brownsville, Texas, and immediately west of the ocean beach known locally as Boca Chica (Tanner and Demirpolat, 1988). The island is made up of 30-odd beach ridges (Fig. 6). These ridges were trenched and sampled in the summer of 1986, and the grain size data were treated to produce ordinary moment measures, various sample suite parameters (Tanner, 1986) and relative moment measures (Demirpolat, Tanner, and Clark, 1986). There is no visible grouping of ridges into sets as is so obvious on St. Vincent Island. Therefore one might well infer that only one ridge set is present, and that there have

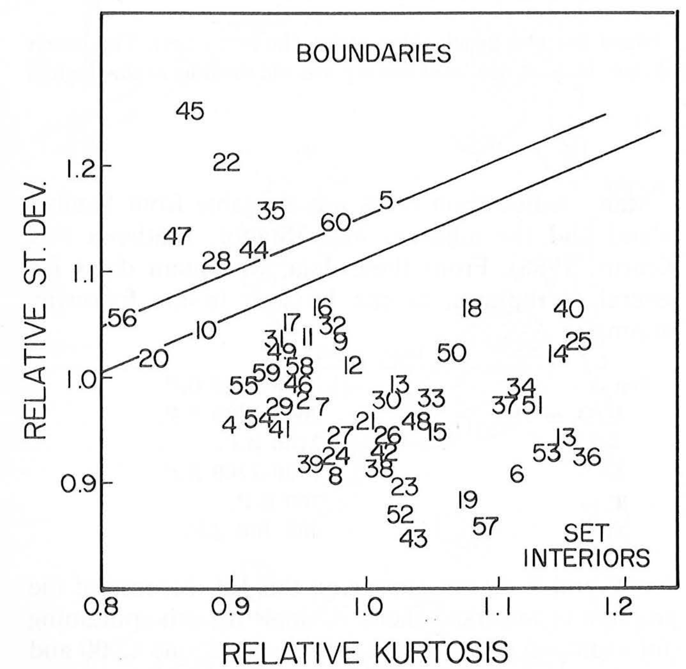

Figure 4-A. Relative standard deviation plotted against relative kurtosis for each sample (for definitions, see text). These relative measures tend to remove sand-pool evolution effects, and therefore to make ridge-to-ridge, or set-to-set, changes obvious. ALL points above and to the left of the diagonal lines represent ridge set boundaries; ALL set interiors plot below and to the right of the diagonal lines. The numbers identify individual beach ridges. The changes shown by "high relative standard deviation and low relative kurtosis" are the same changes obtained on the modern beach during storm surges (change in sea level). However, the events shown here, some 20-50 years long, cannot have been storms, and must have been sea level changes.

been no sea level changes greater than about 50 cm (20 in.) during the construction of this island.

All of the statistical parameters (grain size data) for Mesa del Gavilan are interesting, but the most useful ones — in the present context — are the relative moment measures, particularly the relative standard deviation and the relative kurtosis. These parameters, for Mesa del Gavilan sands, were plotted directly with the St. Vincent Island data (which fall into two distinct number fields: ridge set boundaries, and ridge set interiors). The St. Vincent Island data could be verified by other means, as stated in a previous section. The Mesa del Gavilan ridges showed the same division: the oldest and youngest samples plot with sea level change, and the rest with stable sea level.

Because the Boca Chica sub-delta, on which the island was built, is but the latest in a series of late Holocene sub-deltas (Lohse, 1958), it should be only about 700 – 1200 years old. Mesa del Gavilan can be no older than the sub-delta, and in fact its oldest beach ridge should be not quite as old as that sub-delta. Therefore the history of this one island indicates a sea level rise some 700 – 1000 years ago.

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This is LINEAR-S.  Data source:STVIN.4AE.  N is  37 .  Mn/Ku Cut-off: .68
Std.D/Ku Cut-off:  .115 .   Mn/Ku MovAvgs Window = 3;  mean:  .7131271 .

  I     Std.D./K      Mean     Kurt.   Mn/Kurt. Mov.Avg. (incl. $)        I
Mean value of Mn/Kurt.:                                    #

  1     .096         2.318    3.928                                       1
  2     .106         2.362    3.578     .619   LOW?    $                  2
  3     .103         2.274    3.728     .667   LOW?        $              3
  4     .12     @    2.346    3.158     .662   LOW?        $              4
  5     .135    @    2.23     3.459     .677   LOW?         $             5
  6     .101         2.381    3.658     .665   LOW?        $              6
  7     .119    @    2.392    3.403     .692                 $            7
  8     .113         2.445    3.355     .729                     $        8
  9     .13     @    2.473    3.266     .765                        $     9
 10     .15     @    2.338    2.861     .792                          $  10
 11     .143    @    2.434    3.019     .793                          $  11
 12     .136    @    2.315    3.048     .74                       $      12
 13     .109         2.303    3.455     .703                  $          13
 14     .123    @    2.297    3.33      .649   LOW?      $               14
 15     .096         2.355    3.924     .643   LOW?      $               15
 16     .12     @    2.293    3.542     .63    LOW?     $                16
 17     .122    @    2.212    3.406     .615   LOW?   $                  17
 18     .11          2.14     3.844     .613   LOW?   $                  18
 19     .088         2.435    3.819     .651   LOW?       $              19
 20     .138    @    2.306    2.897     .704                  $          20
 21     .106         2.416    3.449     .741                      $      21
 22     .156    @    2.203    2.992     .796                           $ 22
 23     .146    @    2.415    2.39      .813                            $23
 24     .112         2.365    3.198     .772                        $    24
 25     .106         2.427    3.742     .71                    $         25
 26     .112         2.454    3.255     .731                     $       26
 27     .116    @    2.518    3.121     .785                         $   27
 28     .151    @    2.238    2.8       .817                           $ 28
 29     .126    @    2.468    2.918     .817                           $ 29
 30     .117    @    2.531    3.136     .834                            $30
 31     .135    @    2.474    2.901     .817                           $ 31
 32     .132    @    2.35     2.962     .807                          $  32
 33     .116    @    2.457    3.153     .78                        $     33
 34     .11          2.566    3.327     .766                      $      34
 35     .151    @    2.188    2.931     .7                    $          35
 36     .096         2.228    3.714     .649   LOW?      $               36
 37     .107         2.19     3.523                                      37

Mean value of Mn/Kurt.:                                    #
  I     Std.D./K      Mean     Kurt.   Mn/Kurt. Mov.Avg. (incl. $)        I

This is LINEAR-S.  Data source:STVIN.4AE.  N is  37 .  Mn/Ku Cut-off: .68
Std.D/Ku Cut-off:  .115
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Figure 4-B. Plot of the parameter mean/kurtosis, for part of the data from St. Vincent Island. Note that low beach ridge sets are well-identified by this parameter, which (from modern beaches) is a measure of wave energy density, hence wave height. "Low" and "high" positions lasted for centuries, hence this plot shows sea level changes.

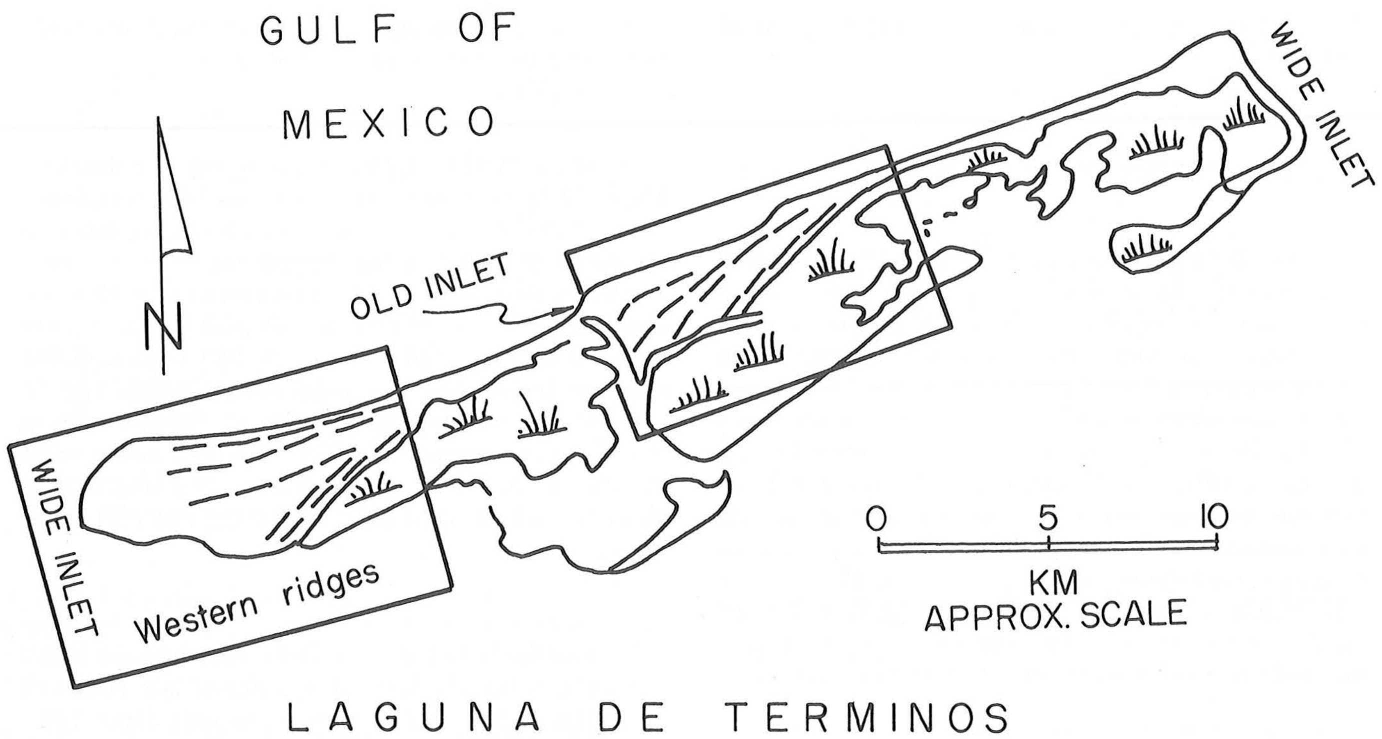


Figure 5. Isla del Carmen, in the state of Campeche, Mexico. The island has two beach ridge plains (box outlines). The beach ridges do show changes in sea level, but those changes have not been dated. Instead, sea level history was obtained by archeological work on the island. The record extends back more than 2,000 years.

SANIBEL ISLAND

The beach ridge plain on this island, on the lower west coast of the Florida peninsula, was not deposited in straight-forward sequential patterns as on St. Vincent Island. On the latter, quartz sand was swept ashore into a series of beach ridges where—for any ridge pair—the younger lies seaward of the older. Therefore the sequence is easy to decipher, there are few if any uncertain time relationships, and the system does constitute a calender.

On Sanibel Island (Fig. 7), the shell debris making up the ridges was deposited in patterns where sequences are not easy to establish, or in some instances are impossible to ascertain. For example, ridge set E was followed by set F (cf. Missimer, 1973, where the sets are numbered), but set G was added near the southern end of F and set H was deposited near the northern end of E. Set H does not touch or even come within a kilometer (0.6 mile) of F (or within 4.5 km, 2.7 mi, of G). Therefore one cannot deduce, from the pattern alone, the time sequence within the system F-to-H.

A similar problem involves Set C vs. Set D, and C vs. E. It is clear that set A is the oldest, and H, I and J are the youngest. But in between, there is a good deal of uncertainty and possible confusion.

Many radiocarbon dates are available from Sanibel Island and the adjacent area (Stapor, Mathews and Kearns, 1988). From these data, we obtain dates for several of the sets, as can be seen in the following summary:

Set A	3100-3700 B.P.
B/D, or D-1	2600-2800 B.P.
B/C or C	2100 B.P.
D-2	1900-2200 B.P.
F/G	700 B.P.
G	400-700 B.P.

Sets E and F do not appear on this list, because of the problem of reworked shells. A single deposit containing (for example) eight shells 2,000 years old, one 4,000 and one 6,000, should be dated with the youngest cluster: in this example, 2,000 years, and not with re-worked older shells. E and F do not have obvious "youngest clusters," and (pending additional work) their ^{14}C ages are not well known.

Sets C and D do not touch each other (second paragraph, this section). We can say—from map geometry—that C is younger than B, and that D is younger than B, but we cannot determine from the pattern whether C is the youngest of these three sets or whether D is. According to the carbon-14 data, C may be the youngest, and the sequence perhaps should be A-B-D-C.

Each ridge set has a ridge-set elevation, which can be determined in the field or from suitable air photos (cf. Fig. 8). Therefore we have the following scheme:

Set A 3100 - 3700 B.P.	**Lowest**
D 2600 - 2800	**Higher**
D 1900 - 2200	**Highest**
C-? 2100	**Highest**
F 1000 or more	**Low**
G 400 - 700	**High**
H,I,J < 500	**High**

Sets B and E were not used in this compilation.

There are several gaps in the time sequence. The interval that is indicated between Set A and Set D is at least 300 years, and this relatively narrow gap was obtained with inadequate sampling. More detail might well narrow the gap. But the interval from Set C to Set F is more than 1000 years long (or, if taken from Set D, perhaps 900 years long). This interval may be an artifact of the sampling pattern: seven different localities on adjacent islands show that beach ridges were being built during this time. Therefore a reasonably continuous history can be pieced together, despite the nonsequential pattern.

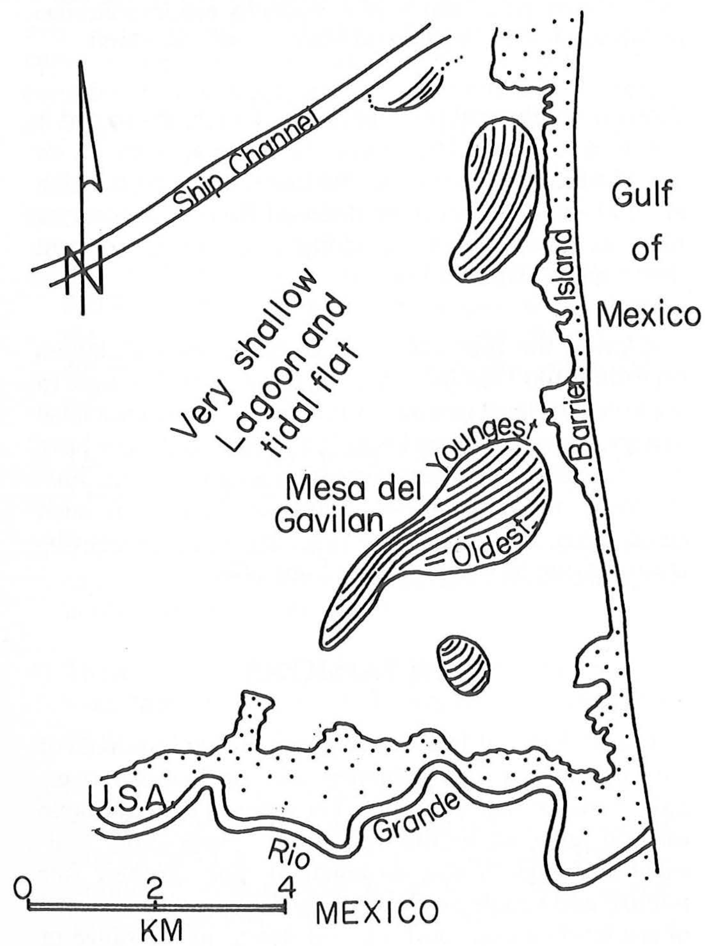


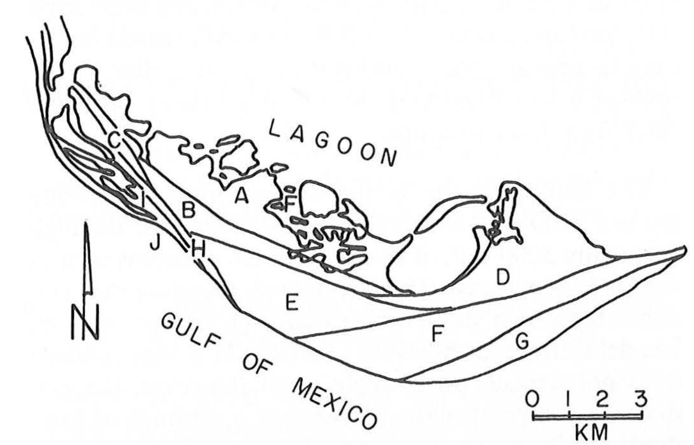
Figure 6. Mesa del Gavilan, in the southern part of Laguna Madre, east of Brownsville, Texas. Four beach ridge plain islands are shown; one was studied in detail. The ridges were built, by wind tides, from the lagoon side, not from the Gulf of Mexico side. This beach ridge plain shows a rise in sea level some 800 - 1000 years ago, but no events earlier than that; presumably the record of earlier history was buried under river delta deposits.

That history is summarized in the list of "high" and "low" stands above. It agrees in every position with the results obtained from the St. Vincent Island study.

NORTHEASTERN MEXICO

A single high stand, with a ^{14}C date of 1800 - 2100 B.P., was reported by Behrens (1966). The critical material indicates a sea level position roughly 2 m (6.7 ft) above the present one. The site is located near Soto la Marina, east of Ciudad Victoria, in the state of Tamaulipas, Mexico. No one of us has visited the site, but it is worth mentioning because it provides one point of pertinent data from a part of the Gulf of Mexico coast well removed from our study localities.

The Soto la Marina locality also provides an old high stand farther back in time than any part of the record at Mesa del Gavilan (Texas), almost 300 km (180 mi) to the north. This high stand, although not matched on the short record at Mesa del Gavilan, is in agreement with the results obtained elsewhere by us, and notably on Sanibel Island in Florida, to the east.



Adapted from Missimer, 1973

Figure 7. Sanibel Island, Fla. Capital letters identify the beach ridge sets. Scores of radiometric dates are available from this island, outlining in fair detail a history covering more than 3,000 years, including two rises and one fall. The beach ridge sets here, however, are not arranged as systematically as on St. Vincent Island; for the problem which this raises, see discussion in text.

SUBMERGED BEACHES

When sea level changes by a few meters (e.g. 1, 2 or 3), the abandoned beach is exposed to either subaerial agencies or considerable wave action. A rise in sea level of this magnitude ordinarily means that wave action will destroy the old beach in short order. Under moderate-to-high wave energy regimes, destruction may not take more than some decades or a few centuries.

However, along a "zero energy" shore—such as the one between Tampa and Tallahassee, Fla.—wave action is so slight that old submerged beaches may be preserved for long periods of time. Such beaches have been mapped in that area (Tanner and Bates, 1965). They exist at about −2 to −3 m (−6.7 to −10 ft), −6.5 m (−22 ft), −8 m (−27 ft), −10 m (−33 ft) and −12 m (−40 ft). No datable materials were found in that study, so one does not know their relative ages, and certainly a sequence cannot be established. However, it is thought from the St. Vincent Island work that sea level has not dropped, in the last 5000 years, more than about 3 or 4 m (10 to 13 ft). Therefore at least one of these submerged shorelines is tentatively assigned to Holocene time. The shallowest, at 2 to −3 m (−6.7 to −10 ft), may have been occupied at least twice. On the sea level curve presented here, it is taken to represent the low stands at about 4500 - 2700 B.P. and about 1700 - 800 B.P.

SYNTHESIS

The St. Vincent Island sea level curve is the longest one in the four study areas, going back to a high stand (+1.5 to +2.5 m; +5 to +8.3 ft) much more than 3500 B.P., perhaps around 5000 B.P., and with details beginning to appear about 3500 B.P., or a bit earlier, at the time of a low stand (Fig. 8). On this history there are three rises and two drops.

The Sanibel curve is the second longest, starting around 3500 B.P. with a low stand. Except for the high at roughly 5000 B.P., it shows all of the positions seen in the St. Vincent area. The last named, therefore, has evidence for a high stand earlier than was seen on Sanibel, Isla del Carmen or Mesa del Gavilan. This high position does not depend on a single point, however; the evidence is visible at many places over a distance of hundreds of kilometers, as discussed in an earlier section.

The Isla del Carmen curve is based largely on the archeological data of Alvarez (1984, 1985). It starts with a high at roughly 2400 B.P., followed by a low at about 1700 B.P., and then one rise (800 B.P.) to the present position. The Mesa del Gavilan curve has a single rise to the modern position, at roughly 800 - 1000 years ago. This latest rise appears in all four areas. The latest drop

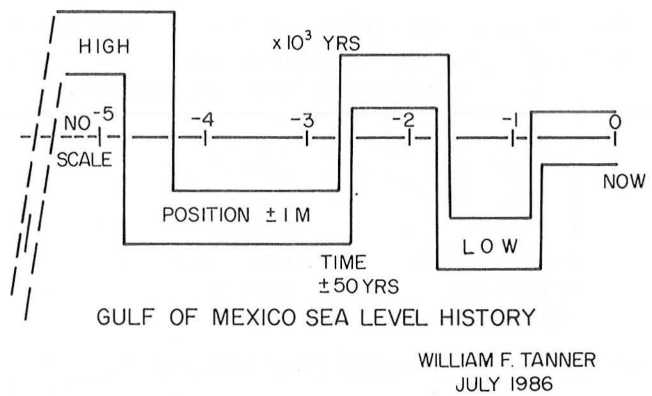


Figure 8. The Gulf of Mexico sea level curve, drawn primarily from St. Vincent Island data, but supported by information from the other three study areas. No time scale is shown earlier than roughly 5,000 B.P. The curve is constrained by four dates, but interpolation is based on the highly regular pattern of the beach ridges on the island: one roughly every 20 - 30 years (but, because of accessibility and identification problems, the sampling interval was every 40 - 60 years).

shows up in three of the four; in the fourth, the record is not long enough. The next-to-last rise appears in, or must be inferred in, three of the four areas. And the high at 5000 - 6000 B.P. can be deduced from field observations at many places, in addition to the St. Vincent Island area (Stapor, 1973).

Because the four areas are scattered over distances exceeding 1000 km (621 mi), the cause of the changes in apparent sea level position is taken to be actual sea level history, rather than local warping, which could not have been so well coordinated over such long distances. Furthermore, the up-and-down nature of the data, in such small areas, in a very short time frame, precludes distractions due to warping or tectonic effects.

CONCLUSIONS

The St. Vincent Island area has provided hundreds of data points in a time sequence, with no hiatuses, overlaps or major discontinuities. The types of data available on and adjacent to this island are topographic, sedimentologic (grain size parameters), photographic (air photos) and pedologic. All of these data provide a record of sea level change, both up and down, in the range of about one meter (3.3 feet) to perhaps as much as 3 - 4 m (10 - 13.3 ft). Three rises and two drops are obvious, within the latest 6000 years. Changes as small as 50 cm (20 in.) probably cannot be detected by the methods at hand, so the history obtained to date is probably incomplete. It is highly unlikely, with hundreds of data points in a small study area, that major changes (one meter, i.e. 3.3 feet, or more) have been overlooked.

Additional work on beach ridges in three other areas, using ^{14}C dates, air photo analysis, granulometric inference and archeological studies, has produced the same sea level history that was obtained on St. Vincent Island, as far back as the record goes in each place. These other areas, in the order of their record lengths, are Sanibel Island, Isla del Carmen and Mesa del Gavilan. In addition, there are many points, outside of the four study areas, where the high stand about 5000 years ago left a wave-cut scarp (discussed in a previous section) that can be seen now.

There is also positive evidence for a Holocene sea level position at −2 or −3 m (−6.7 to −10 ft). It is thought that the submerged beach at −2 to −3 m (−6.7 to −10 ft) represents the low position 1000 - 1800 years ago, and perhaps also the low 3000 - 4500 years ago.

We would like to designate our detailed sea level history as the "Gulf of Mexico" late Holocene sea level curve, to emphasize the fact that it can no longer be considered to be local, and therefore possibly the result of warping, compaction or other local effects.

As far as the Gulf of Mexico region is concerned, we can now make certain general statements.

1) The middle-to-late Holocene sea level curve was NOT asymptotic from below, despite statements to that effect in many papers (using procedures not capable of such fine resolution as the beach ridge work).

2) There were several important fluctuations, in the 1 - 5 m (3.3 to 16.7 ft) range.

3) Changes less than some 50 cm (20 in.) apparently cannot be identified with any assurance, using the kinds of data available to us.

4) There appears to be a quasi-periodicity in the data, with "periods" having been very roughly 2000 years long.

5) Grain-size data provide a great deal of information about stability of sea level, or the lack of it, for intervals as small as 10 - 50 years. Such data show the timing, direction, and duration of each change (greater than about 50 cm, or 20 in.).

6) The many data points from simple beach ridge plains (like St. Vincent Island where the sequence of ridges is clear) provides much higher assurance than can be obtained by using one or two points from some other kind of coastal setting.

7) Quartz sand beach ridges provide one distinctive kind of information (hydrodynamic; as seen in grain-size moment measures), and shell ridges provide another (radiometric dating). Where both ridge types agree, as in the present study, the assurance is great.

8) The use of a very large number of data points—such as 500 or 1000—does not in itself automatically produce useful results. One might elect to treat the entire data set by means of extracting averages or simple trends of some kind, which commonly amounts to throwing away most of the available information. The average position of sea level, over the past 5000 or 6000 years, is not nearly as interesting or useful as systematic departures from that average.

9) Narrow geographic limits for a single study—such as the 6 by 14 km (3.6×8.4 mi) size of St. Vincent Island—provide that one can collect scores or hundreds of data points without having to worry about differential effects, such as warping, tilting, compaction, etc.

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